# Ross procedure: is the root replacement technique superior to the sub-coronary implantation technique? Long-term results

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Abstract: There is controversy over the use of the Ross procedure with regard to the sub-coronary and root replacement technique and its long-term durability. A systematic review of the literature may provide insight into the outcomes of these two surgical subvariants. A systematic review of reports between 1967 and February 2013 on sub-coronary and root replacement Ross procedures was undertaken. Twenty-four articles were included and divided into (i) sub-coronary technique and (ii) root replacement technique. The 10-year survival rate for a mixed-patient population in the sub-coronary procedure was 87.3% with a 95% confidence interval (CI) of 79.7-93.4 and 89.1% (95% CI, 85.3-92.1) in the root replacement technique category. For adults, it was 94 vs 95.3% (CI, 88.9-98.1) and in the paediatric series it was 90 vs 92.7% (CI, 86.9-96.0), respectively. Freedom from reoperation at 10 years was, in the mixed population, 83.3% (95% CI, 69.9-93.4) and 93.3% (95% CI, 89.4-95.9) for sub-coronary versus root replacement technique, respectively. In adults, it was 98 vs 91.2% (95% CI, 82.4-295.8), and in the paediatric series 93.3 vs 92.0% (95% CI, 86.1-96.5) for sub-coronary versus root replacement technique, respectively. The Ross procedure arguably has satisfactory results over 5 and 10 years for both adults and children. The results do not support the advantages of the sub-coronary technique over the root replacement technique. Root replacement was of benefit to patients undergoing reoperations on neoaorta and for long-term survival in mixed series.

DOI: https://doi.org/10.1093/ejcts/ezu176

European Journal of Cardio-Thoracic Surgery 46 (2014) 944–951
doi:10.1093/ejcts/ezu176 Advance Access publication 24 April 2014

**REVIEW**

# Ross procedure: is the root replacement technique superior to the sub-coronary implantation technique? Long-term results

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Received 20 January 2014; received in revised form 17 March 2014; accepted 19 March 2014

## Summary

There is controversy over the use of the Ross procedure with regard to the sub-coronary and root replacement technique and its long-term durability. A systematic review of the literature may provide insight into the outcomes of these two surgical subvariants. A systematic review of reports between 1967 and February 2013 on sub-coronary and root replacement Ross procedures was undertaken. Twenty-four articles were included and divided into (i) sub-coronary technique and (ii) root replacement technique. The 10-year survival rate for a mixed-patient population in the sub-coronary procedure was 87.3% with a 95% confidence interval (CI) of 79.7–93.4 and 89.1% (95% CI, 85.3–92.1) in the root replacement technique category. For adults, it was 94 vs 95.3% (CI, 88.9–98.1) and in the paediatric series it was 90 vs 92.7% (CI, 86.9–96.0), respectively. Freedom from reoperation at 10 years was, in the mixed population, 83.3% (95% CI, 69.9–93.4) and 93.3% (95% CI, 89.4–95.9) for sub-coronary versus root replacement technique, respectively. In adults, it was 98 vs 91.2% (95% CI, 82.4–295.8), and in the paediatric series 93.3 vs 92.0% (95% CI, 86.1–96.5) for sub-coronary versus root replacement technique, respectively. The Ross procedure arguably has satisfactory results over 5 and 10 years for both adults and children. The results do not support the advantages of the sub-coronary technique over the root replacement technique. Root replacement was of benefit to patients undergoing reoperations on neoaorta and for long-term survival in mixed series.

**Keywords:** Heart valves • Ross procedure • Aortic valve replacement • Pulmonary valve replacement

## INTRODUCTION

In the search for an ideal substitute for the aortic valve, a technique of the pulmonary valve implantation in the aortic position was invented. Currently, two modalities of this surgical procedure are accepted: the sub-coronary and root replacement techniques. In the sub-coronary modality, free dissected leaflets of the pulmonary root were implanted in a sub-coronary position in the aortic root [1] (Fig. 1). This, because it is a technically demanding procedure, did not gain wide acceptance [2] among paediatric and adult cardiac surgeons. However, with the invention of root replacement (Fig. 1) in the late 1980s, the Ross procedure underwent a renaissance. The technique whereby the aortic root is replaced with a pulmonary root autograft is technically easier to perform than sub-coronary implantation [1, 2]. Wide acceptance of the root replacement technique was a consequence.

Implantation of the pulmonary root in the aortic root position may be considered a haemodynamically perfect substitute for a native aortic valve; however, the Ross procedure remains a double valve replacement and therefore has all the potential disadvantages of such a procedure. The main concerns four decades after the first implantation are structural and non-structural failures of the pulmonary autograft and of the homograft in the right ventricular outflow tract (RVOT), with a requirement for reinterventions. It was postulated that 15 years after surgery, about a quarter of the implanted pulmonary autografts failed. Age, gender, preoperative aortic root anatomy and the modality of the surgical intervention, sub-coronary versus root replacement technique, were thought to be predictive factors for autograft failure [3, 4]. The sub-coronary technique was considered advantageous over root replacement (Fig. 1).

However, information in recent literature on the long-term outcomes of the two surgical modalities is not conclusive, and there is no randomized study comparing these two Ross modalities. The aim of this systematic review of all available evidence of the Ross procedure with a follow-up of 10 years was to improve our knowledge on the outcomes of the procedure and contribute to the understanding of neoaortic root failure that often occurs following the procedure. The goal is to compare the long-term results of the sub-coronary versus the root implantation techniques in adult, mixed and paediatric populations in order to define the incidence of major cardiovascular events and the failure rate of the neoaortic root and RVOT conduit.

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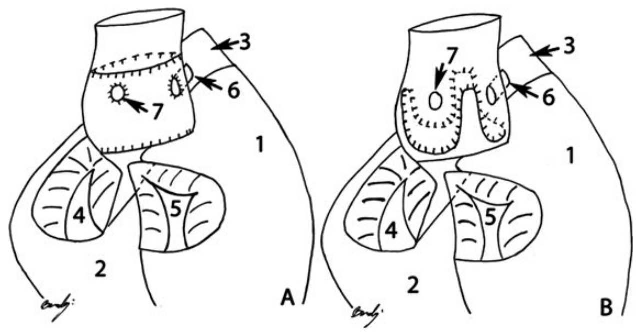


**Figure 1:** Schematic drawing of the root replacement technique (**A**) and sub-coronary implantation technique (**B**). Note in both schematic drawings that the aortic root is viewed from the posterior side. The left and the right atrium were removed. (**A**) The root replacement technique is seen with horizontal suture line at the neoaortic root base and sinutubular junction. In this case, the left and right coronary artery ositum has to be reimplanted into the wall of the neoaortic root. (**B**) Sub-coronary implantation technique is seen. Here, the suture line is positioned under the ostium of the left and right coronary artery. Note that the suture line has a semilunar shape and is placed at nadirs of the native aortic valve leaflets. In this technique, there is no need for reimplantation of the coronary ostia. 1. Right ventricle, 2. left ventricle, 3. pulmonary artery, 4. mitral valve, 5. tricuspid valve, 6. right coronary artery and 7. left coronary artery.

## MATERIALS AND METHODS

### Search strategy

On February 2013, a PubMed and EMBASE search of (aortic valve replacement AND autograft) OR (aortic valve replacement AND Ross procedure) OR (Ross procedure AND pulmonary valve replacement) was conducted, limited to publications from 1967 until 2011 in humans. In addition, the entire Cochrane library was searched for (autograft aortic valve replacement) OR (Ross procedure) OR (Ross procedure AND pulmonary valve replacement) in the title, abstract or keywords of publications. Manuscripts written in English, German and French languages were considered.

Two reviewers (Mirza Muradbegovic and Daniel Haselbach) screened the titles and abstracts of identified studies. A third independent reviewer (Denis A. Berdajs) assessed whether inclusion and exclusion were performed correctly. In case of disagreement, an agreement was negotiated between all three reviewers. References of selected articles were crosschecked for other relevant studies. Authors were contacted when a publication could not be obtained or when additional information was required.

### Inclusion/exclusion criteria

The review included observational studies reporting on mortality and/or morbidity after autograft aortic valve or root replacement, with a completeness of follow-up 90% (high quality), and a study size of $n > 30$, reflecting the centre's experience. In the case of multiple publications on the same patient population, the most recent report was selected.

### Data extraction

Microsoft Excel and Review Manager version 4.2 for Windows (The Cochrane Collaboration, 2003) were used for data extraction and data storage. To control for potential heterogeneity caused by patient age, publications were allocated to the following categories: (i) consecutive series in both children and adults, (ii) adult patient series (adults and/or children aged ≥15 years at the time of the procedure) and (iii) paediatric patient series. The study design is documented for each paper meeting the inclusion criteria. Outcome events were registered according to the 2008 American Association for Thoracic Surgery/Society of Thoracic Surgeons/ European Association for Cardiothoracic Surgery guidelines [5].

### Primary and secondary end points

Primary end points were defined as: in-hospital mortality (within 30 days post-surgery), mortality during follow-up, reoperation rate at long term and short term for neoaorta and RVOT conduit.

Secondary end points were defined as the incidence of a major cardiovascular event (thromboembolic event and myocardial infarction), rate of neoaorta endocarditis and incidence of structural and non-structural deterioration of the neoaorta and RVOT conduit. Structural valve deterioration and nonstructural valve deterioration were diagnosed either at reoperation or at autopsy with regard to the surgical implantation technique.

Preoperative factors such as, age, gender, indication for surgery and previous interventions were investigated to identify predictive factors for neoaorta and RVOT reintervention in sub-coronary versus root replacement technique.

Data on survival, event-free survival and reoperation were required to be available for a follow-up period of more than 5 years in order for a study to be included in this systematic review.

### Statistical analysis

Descriptive statistics for the population characteristics of the included studies, i.e. year of study, number of patients, mean patient age and range, gender distribution, New York Heart Association (NYHA) classification and preoperative ejection fraction are displayed. Results of the outcomes are considered in groups of combinations between patient series (mixed, adult, child) and procedure (Ross, sub-coronary; Ross, root replacement). The primary and secondary end points are proportions of patients with specific conditions; therefore, the single individual proportions are displayed per study, together with an overall pooled estimate of the proportion. A random effects model was assumed to account for unexplained heterogeneity between studies, and the DerSimonian–Laird estimator was used for between-study variance ([6], p.285ff.). All statistical analyses were performed with R for Windows [7].

## RESULTS

Searching the databases for the relevant mesh terms led to 870 publications. Through the reading and evaluation process, 212 manuscripts were found to be suitable for inclusion. Thirty-five manuscripts were excluded for the following reasons: number of cases was <20 ($n = 6$), overlap with other studies ($n = 4$), no specification of the Ross procedure technique ($n = 10$), only abstract published ($n = 15$). Consequently, the full-text was retrieved for 177 studies and data were extracted. Of these, 73 studies had reported on survival with a follow-up of more than 5 years. Event-free survival for a follow-up of more than 5 years was reported in 31

**Table 1:** Publications overview

| Author | Year of publication | Time span | Number of patients | Procedure | Follow-up (months) | Mean age of patients (years) | Age range (years) |
|---|---|---|---|---|---|---|---|
| Somerville | 1979 | 1967–1972 | 85 | Ross 1 | | 33 | 12–54 |
| Gula | 1979 | 1967–1977 | 188 | Ross 1 | | 30 | 9–64 |
| Matsuki | 1988 | 1967–1986 | 241 | Ross 1 | | | 9–60 |
| Chambers | 1997 | 1967–1984 | 131 | Ross 1, 2 | 240 | 32 | 11–52 |
| Elkins | 1999 | 1987–1999 | 244 | Ross 2 | 36 | 22 | 0–62 |
| Knott-Craig | 2000 | 1986–1999 | 145 | Ross 2 | 30 | 35 | 17–82 |
| Elkins | 2001 | 1986–2001 | 178 | Ross 1,2 | 62.6 | 9.6 | 0–17 |
| Oswalt | 2001 | 1990–2001 | 191 | Ross 2 | | | 0–69 |
| Sievers | 2003 | 1994–2002 | 245 | Ross 1 | 29.4 | 45.7 | 15–70 |
| Takkenberg | 2005 | 1988–2003 | 47 | Ross 2 | 73 | 8 | 0.25–15 |
| Settepani | 2005 | 1991–2003 | 103 | Ross 2 | 72 | 35.2 | 17–65 |
| Sampath | 2005 | 1993–2003 | 153 | Ross 2 | 77 | 28 | 0.7–65 |
| Hazekamp | 2005 | 1994–2003 | 53 | Ross 2 | 66 | 9.7 | 0–17.7 |
| Ruzmetov | 2006 | 1991–2001 | 81 | Ross 2 | 92.4 | 31 | 16–52 |
| Kumar | 2006 | 1993–2003 | 81 | Ross 2 | 92.3 | 29.5 | 11–56 |
| Sievers | 2006 | 1994–2005 | 347 | Ross 1 | 45.6 | 44 | 14–71 |
| Da Costa | 2006 | 1995–2005 | 227 | Ross 1,2 | 45.5 | 29.1 | 5–56 |
| Klieverik | 2008 | 1987–2007 | 63 | Ross 2 | 123.6 | 29 | 16–52 |
| Favarolo | 2008 | 1995–2006 | 165 | Ross 2 | 57 | 39 | 16–65 |
| Özaslan | 2008 | 1996–2007 | 50 | Ross 2 | 74.4 | 50 | 13–63 |
| El Behery | 2009 | 1991–2003 | 41 | Ross 2 | 72 | 10.17 | 0.45–18.3 |
| Da Costa | 2009 | 1995–2006 | 272 | Ross 2 | 67 | 30 | 5–56 |
| Hamamsy | 2010 | 1994–2001 | 108 | Ross 2 | 122.4 | 38 | 19–66 |
| Roura | 2010 | 1995–2008 | 198 | Ross 2 | 69.8 | 39 | 16–65 |

Overview of publications included in analysis.
Ross 1: sub-coronary implantation technique; Ross 2: root replacement technique.

studies, including reoperations with a follow-up of more than 10 years in 26 studies (Table 1). Two studies had no specification on patient age. Thus, 24 studies were included in the detailed analysis and evaluation. Of these, 5 series were related to the isolated sub-coronary technique ($n$ = 1355 patients), 16 series to the root replacement technique ($n$ = 2146 of patients) and 3 series to both sub-coronary and root replacement techniques ($n$ = 536 patients). Adult and mixed series were described in 20 reports on 3718 patients and paediatric in 4 reports on 319 patients.

Further, 13 studies ($n$ = 1719 patients) reported on survival with a follow-up of more than 10 years, 4 studies ($n$ = 861 patients) on the sub-coronary implantation technique and 9 studies ($n$ = 858 patients) on the root replacement technique. Event-free survival for a follow-up of more than 10 years was reported in all 13 studies (Table 1). Table 1 provides an overview of the publications obtained by the review.

Descriptive statistics, including mean and range of study characteristics, are displayed in Table 2. Studies presenting isolated sub-coronary implantation of the pulmonary valve were published between 1979 and 2006, whereas studies reporting results with root replacement technique are from 1999 and 2010. The mean age of patients in studies of the sub-coronary technique was 38.2 (range, 30.0–45.7) years and was 28.9 (range, 8.0–50.0) years for root replacement. Male patients comprised 79.6% (range 78.0–81.9) of sub-coronary studies and 71.1% (55.6–86.8) of root replacement studies. The indication for intervention was stenosis of aortic valve in 27.3% of the overall population. In the sub-coronary procedure, aortic valve stenosis was the indication in 21.5% (range, 13.3–31.5%) of patients, and in 28.4% (range, 4.9–58.1%) for the root replacement technique. Regurgitation was the indication for surgery in 36.9% of the patients overall, 39.5% in the sub-coronary technique patients and 36.4% for root replacement.

Pooled results of the primary and secondary outcomes for groups of studies are given in Table 3, including 5- and 10-year results separately in adult and paediatric cohorts.

## Root versus sub-coronary implantation technique

In the mixed cohort, freedom from in-hospital mortality was 95.8% (CI, 88.6–99.6) for the sub-coronary technique and 95.6% (CI, 93.5–97.0) for the root replacement technique. Survival at 5 years was 96.2% (CI, 92.4–98.1) in the sub-coronary and 96.7% (83.5–99.4) in the root replacement series. At 10 years, this was 87.3% (CI, 79.7–93.4) in the sub-coronary technique patients and 89.1% (CI, 85.3–92.1) in the root replacement patients (Table 3). Freedom from reoperation on neoaorta in the mixed series at 5 years was 95.5% (CI, 90.1–98.0) in the root replacement technique and 90.6% in the sub-coronary technique, at 10 years this was 93.3% (CI, 89.4–95.9) and 83.3% (CI, 69.9–93.4), respectively.

For each of the sub-coronary and root replacement techniques, only one manuscript with a follow-up of 5 years was found that covered RVOT reintervention rates in a mixed population [8, 9]. Sievers *et al*. [9] showed a freedom of reoperation on RVOT of 97% in their series of 347 cases of sub-coronary implantation, which was lower than the rate published by Kumar *et al*. [8], where this value was 100% in the root replacement group. At 10 years, in the root replacement group the freedom from RVOT reoperation was 84.0% (CI, 76.5–89.3) and 77.8% (53.1–95.1) in the sub-coronary technique patients (Table 3). The reasons for RVOT as well as for neo-aorta reoperations are listed in detail in Table 4. In the mixed cohort, freedom from a major cardiovascular event at 5 years was 91.6% (CI, 88.5–93.9) in the sub-coronary technique patients and 86% (CI, 74.1–93.3) in the root replacement technique patients. At

**Table 2:** Summary of population characteristic's

| Study characteristics | Mean (SD) | Range | NA's |
|---|---|---|---|
| Year of publication | 2002 | 1979–2010 | |
| Sub-coronary | 1990 | 1979–2006 | |
| Root replacement | 2006 | 1999–2010 | |
| Mean age of patients at intervention | 30.9 (11.7) | 8–50 | 4 |
| Sub-coronary | 38.2 (7.8) | 30–45.7 | 2 |
| Root replacement | 28.9 (12.0) | 8–50 | 2 |
| Number of patients | 152.2 (85.9) | 41–347 | |
| Sub-coronary | 225.8 (86.1) | 85–347 | |
| Root replacement | 126.2 (71.3) | 41–272 | |
| % Male gender | 72.8% | 55.6–86.8 | 3 |
| Sub-coronary | 79.6% | 78.0–81.9 | 2 |
| Root replacement | 71.1% | 55.6–86.8 | 1 |
| NYHA classification I–II (%) | 65.7% | 25.5–83.5 | 15 |
| NYHA classification III–IV (%) | 33.2% | 14.9–74.5 | 15 |
| Indication for surgery (stenosis) (%) | 27.3% | 4.9–58.1 | 4 |
| Subcoronary | 21.46% | 13.3–31.5 | 3 |
| Root replacement | 28.4% | 4.9–58.1 | 1 |
| Indication for surgery (regurgitation) (%) | 36.9% | 8.6–72.8 | 3 |
| Sub-coronary | 39.5% | 32.0–52.7 | 3 |
| Root replacement | 36.4% | 8.6–72.8 | 0 |
| Indication for surgery (mixed) (%) | 41.3% | 22.2–75.6 | 5 |
| Sub-coronary | 43.4% | 30.6–54.2 | 3 |
| Root replacement | 40.9% | 22.2–75.6 | 2 |
| Previous interventions (ballon) (%) | 13.8% | 0.3–42.6 | 14 |
| Previous interventions (open surgery) (%) | 17.7% | 1.2–46.8 | 10 |
| Associated procedures, total number (%) | 25.0% | 3.7–67.2 | 3 |
| Sub-coronary | 25.9% | 12.9–47.8 | 1 |
| Root replacement | 24.7% | 3.7–67.2 | 2 |
| Duration of cardiopulmonary bypass (min) | 179 | 116–214 | 9 |
| Mean cross-clamp time (min) | 132.2 | 94–174 | 7 |
| Mean duration hospital stay after surgery (days) | 9.9 | 8–12 | 19 |

Descriptive statistics for the 26 studies with more than 5-year follow-up time. Herein, the prepertive and intraoperative variables may be seen.



10 years, this was 84.0% (CI, 76.5–89.3) and 77.8% (CI, 53.1–95.1), respectively (Table 3).

In the adult series (*n* = 8 manuscripts), there were no reports on the sub-coronary technique with 5-year survival, and only one manuscript describing results with a 10-year follow-up on sub-coronary technique was included [10]. Freedom from in-hospital mortality was 99.2% in the sub-coronary technique group and 97.5% (CI, 95.6–98.5) in the root replacement technique group. Survival rate at 10 years in the sub-coronary group was 94% and in the root replacement group was 95.3% (CI, 88.9–98.1). Freedom from neoaorta reintervention was 98% [10] in the sub-coronary group and 91.2% (CI, 82.4–95.8) in the root replacement technique patients. For RVOT, the freedom from reoperation was 97.0% [10] and 95.9% (CI, 90.6–98.3) (Table 3). Freedom from a major cardiovascular event at 10 years was 97% [10] in the sub-coronary group and 87% (CI, 76.5–93.4) in the root replacement group (Table 3).

In the paediatric (age <15 years) series, four publications were included. The sub-coronary technique was evaluated in one report [11], with the follow-up results of 10 years. Freedom from in-hospital mortality was 95.5% in the sub-coronary technique group and 96.3% (CI 91.1–98.5) in the root replacement technique patients. Survival at 10 years was 90% [11] in the sub-coronary and 92.7% (CI, 81.3–97.4) in the root replacement groups [11]. Freedom from neoaorta reintervention was 93.3% [11] in the sub-coronary and 92.9% (CI, 86.1–96.5) in the root replacement technique group. For RVOT, this was 89.9% (9) and 92.6% (90.2–97.9), respectively (Table 3). Freedom from a major cardiovascular event at 10 years was 93.3% [11] in the sub-coronary and 92.9% (CI, 86.1–96.5) in the root replacement group.

Reasons for RVOT as well as for neoaorta reoperations are listed in detail in Table 4.

## DISCUSSION

The Ross procedure is an alternative to aortic valve replacement in adults and in paediatric populations. The advantages of the Ross procedure, compared with the commercially available aortic valve prosthesis, are in its superior haemodynamic performance, minimal incidence of thromboembolic and infective events and potential for growth in paediatric cases. Since the first implantation by Donald Ross [1] in the late 1970s, considerable experience has been accumulated. Currently, two modalities of the surgical technique are accepted: the sub-coronary and root replacement techniques (Fig. 1). The root replacement technique gained acceptance by both paediatric and adult cardiac surgeons due to its less demanding implantation technique and predictability in the short term. Because of the excellent results of root replacement in the short term, in the late 1990s, the ideal substitute for the aortic valve was considered to have been found [2, 3, 9, 11, 12]. However, results over the first 5 years showed that in addition to RVOT

**Table 3:** Mixed, adult and paediatric patient cohorts with primary end points, by procedure and series

| Study | Survival | | | Freedom of major cardiovascular event | | Freedom of reoperation on neoaorta | | Freedom of reoperation on RVOT | |
|---|---|---|---|---|---|---|---|---|---|
| | 30 days | 5 years | Maximal | 5 years | 10 years | 5 years | 10 years | 5 years | 10 years |
| (A) Mixed patients cohort with primary end points, by procedure and series | | | | | | | | | |
| Sub-coronary implantation | | | | | | | | | |
| Somerville (1979) | – | 94 | 87 | 94.1 | 90.6 | 91.8 | 80 | – | 94.1 |
| Gula (1979 | 91 | – | 82 | – | 86.7 | 82.4 | 78.2 | – | 80.9 |
| Matsuki (1988) | 93.4 | – | 83 | – | 40.5 | 85.1 | 74.7 | – | – |
| Sievers (2006) | 99.4 | 97 | 94 (8 years) | 91.0 | 84 | 97.0 | 95 | 97.0 | 95 |
| Overall[a] 95% CI[b] | 95.8 (88.6–99.6) | 96.2 (92.4–98.1) | 87.3 (79.7–93.4) | 91.6 (88.5–93.9) | 77.8 (53.1–95.1) | 90.6 (81.5–) | 83.3 (69.9–93.4) | – | 90.9 (80.5–97.8) |
| Root replacement | | | | | | | | | |
| Elkins (1999) | | 98.0 | 86 | 91.0 | 84 | 98.0 | 95.9 | | 91.8 |
| Oswalt (2001) | 94.8 | | 90.2 | 88.5 | 85.9 | | 91.6 | | 90.6 |
| Sampath (2005) | 93.5 | 88.3 | 86.9 | 75.0 | 68.3 | 91.8 | 87 | | – |
| Kumar (2006) | 92.6 | | 84.4 (9 years) | | 84 | 94.0 | 93 | 100.0 | 100 |
| Özaslan (2008) | 100 | 100.0 | 100 | | 84 | | 90 | | 98 |
| Da Costa (2009) | 97.1 | | 93 (12 years) | | 90.5 | | 97 | | 95 |
| Overall[a] 95% CI | 95.6 (93.5–97.0) | 96.7 (83.5–99.4) | 89.1 (85.3–92.1) | 86.4 (74.1–93.3) | 84.0 (76.5–89.3) | 95.5 (90.1–98.1) | 93.3 (89.4–95.9) | – | 93.8 (90.2–96.1) |
| Sub-coronary and root replacement | | | | | | | | | |
| Chambers (1997) | 97.7 | – | 85 | – | 26.7 | – | 89.3 | – | 89.3 |
| Da Costa (2006) | 96.5 | 94.2 | 93.5 | – | 89.4 | – | 96.4 | – | 96.2 |
| Overall[a] 95% CI | 97.2 (94.8–98.5) | – | 90.4 (78.8–96.0) | – | 63.7 (7.5–97.5) | – | 93.7 (82.3–97.9) | – | 93.7 (82.3–97.9) |
| (B) Adult patients cohort with primary end points, by procedure and series | | | | | | | | | |
| Sub-coronary implantation | | | | | | | | | |
| Sievers (2003) | 99.2 | – | 94 | – | 97 | – | 98 | – | 97 |
| Root replacement | | | | | | | | | |
| Knott-Craig (2000) | 94 | 97 | 77 | 91 | 73 | | 87.6 | – | 87.6 |
| Settepani (2005) | 100 | | 97.3 | 96.3 | 75.4 | 98.7 | 87.4 | – | 98.7 |
| Ruzmetov (2006) | 97.6 | | 97.4 | | 98.7 | | 87 | – | – |
| Klieverik (2008) | 96.8 | | 96.8 (13 years) | | 59.2 | 100.0 | 63.4 | – | – |
| Favarolo (2008) | 97.5 | | 94.8 | | 91 | | 96.3 | – | 100 |
| El-Hamamsy (2010) | 99 | 97 | 97 | | 96.2 | 100.0 | 99 | – | 95 |
| Roura (2010) | 97.5 | | 94.8 | 91 | 91 | | 95 | – | 95 |
| Overall[a] 95% CI | 97.4 (95.6–98.5) | 97.2 (94.3–98.7) | 95.3 (88.9–98.1) | 92.6 (88.2–95.4) | 87.1 (76.5–93.4) | 99.2 (97–99.8) | 91.2 (82.4–95.8) | – | 95.9 (90.6–98.3) |
| (C) Paediatric patients cohort with primary end points, by procedure and series | | | | | | | | | |
| Root replacement | | | | | | | | | |
| Takkenberg (2005) | 100 | 93.0 | 93 | 97.0 | 92 | 93.6 | 91.5 | 93.6 | 89.4 |
| Hazekamp (2005) | 94.4 | 92.4 | 89 | 93.0 | 89 | 93.0 | 89 | 97.0 | 97 |
| El Behery (2009) | 95 | 95.0 | 95 | 85.3 | 75.7 | 100 | 100 | 97.0 | 89 |
| Overall[a] 95% CI | 96.3 (91.1–98.5) | 93.5 (88.0–96.6) | 92.7 (86.9–96.0) | 92.8 (81.3–97.4) | 88.0 (75.6–94.5) | 95.6 (90.2–98.1) | 92.9 (86.1–96.5) | 95.6 (90.2–97.9) | 92.6 (85.4–96.4) |
| Sub-coronary implantation | | | | | | | | | |
| Elkins (2001) | 95.5 | – | 90 (12 years) | – | 73 | – | 93.3 | – | 89.9 |

All numbers in percent. Note that all numbers are expressed in %.
[a]Random effects model, DerSimonian-Laird estimator for between study variance.
[b]Confidence interval.

**Table 4:** Mixed, adult and paediatric patient cohorts with secondary end points, by procedure and series

| Study | Neoaorta pathology | | | RVOT | | |
|---|---|---|---|---|---|---|
| | Infection rate | Structural deterioration | Non-structural deterioration | Stenosis | Insufficiency | Non-specified |
| (A) Mixed, patients cohort with secondary end points, by procedure and series | | | | | | |
| Sub-coronary implantation | | | | | | |
| Somerville (1979) | 8.2 | 5.9 | 7.1 | 1.2 | 4.7 | – |
| Gula (1979) | 2.1 | 2.1 | – | – | – | – |
| Matsuki (1988 | 5.8 | – | 6.6 | – | – | – |
| Sievers (2006) | 1.2 | 1.2 | – | 0.9 | 0.9 | – |
| Overall[a] 95% CI[b] | 3.7 (1.7–7.8) | 2.7 (0.7–5.9) | 7.0 (4.4–10.0) | 0.9 (0.4–2.5) | 2.3 (0.6–9.0) | – |
| Root replacement | | | | | | |
| Elkins (1999) | 0.4 | 1.2 | 1.2 | – | – | – |
| Oswalt (2001) | 2.1 | 6.3 | 1.6 | 1.0 | – | 3.1 |
| Sampath (2005) | 3.3 | 4.6 | 0.7 | – | – | – |
| Kumar (2006) | 1.2 | 6.2 | 0.0 | 0.0 | 0.0 | 0.0 |
| Özaslan (2008) | 4.0 | 4.0 | 6.0 | 2.0 | 0.0 | – |
| Da Costa (2009) | 1.5 | 0.7 | 0.4 | 1.5 | 0.0 | – |
| Overall[a] 95% CI | 2.4 (1.5–3.9) | 3.7 (1.9–6.9) | 1.7 (0.9–3.3) | 1.2 (0.6–2.6) | 0.5 (0.1–2.3) | 2.3 (0.7–7.7) |
| Root replacement and sub-coronary implantation | | | | | | |
| Chambers (1997) | 6.1 | 2.3 | 20.6 | 15.3 | 3.1 | – |
| Da Costa (2006) | 0.4 | 1.8 | 0.4 | 1.8 | – | – |
| Overall[a] 95% CI | 2.0 (0.2–21.4) | 2.6 (1.3–4.8) | 3.7 (0.1–67.2) | 5.6 (0.6–36.2) | – | – |
| (B) Adult patients cohort with secondary end points, by procedure and series | | | | | | |
| Sub-coronary implantation | | | | | | |
| Sievers (2003) | 0.4 | 0.4 | 0.4 | 0.8 | 0.8 | – |
| Root replacement | | | | | | |
| Knott-Craig (2000) | 0.7 | 2.1 | – | – | – | – |
| Settepani (2005) | 1.0 | 4.9 | 0.0 | 1.0 | 0.0 | 1.0 |
| Ruzmetov (2006) | 1.2 | 13.6 | 0.0 | – | – | – |
| Favarolo (2008) | 0.0 | 25.4 | 0.0 | 0.0 | 0.0 | – |
| Klieverik (2008) | 0.0 | 0.6 | 0.6 | – | – | 7.9 |
| Roura (2010) | 0.5 | 0.9 | 0.0 | 0.0 | 0.0 | – |
| El-Hamamsy (2010) | 0.0 | 1.0 | 0.5 | 5.6 | 0.9 | – |
| Overall[a] 95% CI | 1.1 (0.5–2.1) | 4.1 (1.4–11.4) | 0.5 (0.2–1.5) | 1.1 (0.2–6.0) | 0.5 (0.1–1.7) | 4.4 (1.1–16.0) |
| (C) Paediatric patients cohort with secondary end points, by procedure and series | | | | | | |
| Sub-coronary implantation | | | | | | |
| Elkins (2001) | 0.6 | 4.5 | 2.2 | 4.5 | 3.9 | – |
| Root replacement | | | | | | |
| Takkenberg (2005) | 0.0 | 2.1 | 2.1 | 2.1 | – | 2.1 |
| Hazekamp (2005) | 0.0 | 9.4 | 0.0 | 5.7 | 0.0 | 5.7 |
| El Behery (2009) | – | 0.0 | 0.0 | 9.8 | 0.0 | – |
| Overall[a] 95% CI | – | 4.4 (1.2–15.0) | 1.5 (0.4–5.8) | 5.3 (1.8–10.2) | – | 3.8 (0.7–8.8) |

All numbers in percent. Note that all numbers are expressed in %.
[a]Random effects model, DerSimonian-Laird estimator for between study variance.
[b]Confidence interval.

conduit failure, there was also considerable rate of neoaortic root deterioration with need for reintervention [9,11,13]. More comprehensive analysis of the long-term results, including one meta-analysis, indicated that surgical technique, female gender, age, preoperative aortic valve pathology (such as bicuspid valve or annular dilatation) were predictive factors for neoaorta dilatation [3,10,11, 14].

A recent analysis focused on the impact of two Ross procedure modalities on survival and reoperation rates. The surgical technique of pulmonary valve implantation into the left ventricular outflow tract was considered one of the independent variables that may influence the long-term durability of the pulmonary valve in the aortic position. The sub-coronary technique was advocated as a preventive factor for late root dilatation and consequent neoaorta structural deterioration [10,11]. However, because of its complexity, this procedure is not broadly accepted. In the present review, in adult and pediatric populations, one-series on sub-coronary implantation technique was found. In contrast in mixed populations six papers on both techniques were included.

The root replacement technique was described in 18 manuscripts included in this review, and in most cases a freestanding root implantation technique was used (in two manuscripts there was no age specification of the cohort). This technique was particularly widely used in the early 1990s. Later, with the accumulation of evidence of long-term survival, neoaortic root dilatation became more obvious. The rate of neoaortic root dilatation was estimated at 0.5 mm/year [15] in an adult and 2 mm/year in a mixed population [16]. The preoperative aortic valve regurgitation was identified as an independent predictive factor [17] for neoaorta dilatation. The dilatation of the aortic root supporting structures at the distal anastomosis line may be a reason for this late dilatation. The medical history of hypertension was not found as a predictive factor, for ne-aorta dilatation [17].

To prevent the neoaorta dilatation, different modalities of root replacement technique were applied, for example, reinforcement with pericardial or Dacron strips at the level of the proximal suture line became popular [8, 12, 18]. However, in most cases, dilatation did not occur at the level of the root base but rather at the level of the three sinuses and the sinutubular junction [9,14, 18].

No explanation was found for this phenomenon; on the one hand, it is obvious that in case of the accompanied ascending aorta and/or sinutubular junction dilatation, replacement of the ascending aorta with a Dacron tube may have a stabilization effect on the distal suture line [8, 12].

Further, considering the natural asymmetry of the aortic and pulmonary roots, the pulmonary root should be implanted in the following manner: the left pulmonary sinus in the position of the right coronary sinus; the anterior pulmonary sinus should be located in the position of the non-coronary sinus; right pulmonary sinus in the position of left coronary sinus [19–22]. It has yet to be proved whether this implantation technique can avoid root dilatation in clinical scenarios.

The dilatation of the neoaorta sinuses following the root replacement was the issue of discussion for years. To prevent this phenomenon, numerous surgical techniques of neoaorta reinforcement have been proposed. The root inclusion technique is one of the most accepted techniques. Here, the pulmonary root is included as whole cylinder inside of the native aortic root. This technique indeed may prevent the late dilatation; however, for objective assessment, there is a net deficit of manuscripts with long-term results on this technique. For example, in our review only two manuscripts describing this surgical technique were included [23, 24].

However, based on our results, we can state that in the mixed population pool the root replacement implantation technique is of advantage compared with the sub-coronary implantation technique at 5 and 10 years. This is true of the neoaorta reoperation rate, freedom from major cardiovascular events and of the RVOT reoperation rate. The higher reoperation rate in the sub-coronary implantation technique is explained by the four times higher rate of non-structural deterioration of the root (Table 4). Additionally, incidence of neo-aorta endocarditis was higher for the sub-coronary technique (Table 4). It would be interesting to determine whether the same phenomenon may be evoked in adult and paediatric series. Unfortunately, it was not possible to cover this in the present review due to a lack of long-term results for these populations. Namely in adult as well as in paediatric population only one report dealing with 10-year results on sub-coronary technique was found [10, 11]. This is a limitation of the recent report, and only randomized studies in both age groups would confirm or disapprove our observation in a mixed population.

The advantage of the root replacement technique regarding the neoaorta reoperation in the mixed population is not surprising; in sub-coronary implantation only the pathological aortic valve is cured by replacement of the pulmonary valve. Diseased aortic root including intervalvular triangles, wall of the sinuses, sinutubular junction and aortic root base rest *in situ*, and thus does negatively influence the function of the neoaortic root. A combination of net pulmonary leaflets implanted into the diseased aortic root components may be the key haemodynamic and morphological element that finally leads to valve dysfunction and structural deterioration. However, this hypothesis should be proved with further clinical and experimental trials.

To reconstruct the RVOT in most cases, pulmonary homograft was implanted, only in a few cases stentles biological valve, and bovine jugular conduit graft were used. It appears from this study that the rate of reoperation on RVOT is in some instances higher in children than in adult or mixed populations. In the mixed series, the degeneration of the RVOT conduit including stenosis and the insufficiency of the conduit valve were predominant reasons for reoperation. A higher insufficiency rate was registered in the sub-coronary technique group (Table 4) compared with the root replacement technique group. Incidence was similar in mixed and adult populations; however, in the paediatric series the reoperation rates were about 4.5 times higher with predominance of the stenosis on the RVOT conduit. This, in part, may be explained by the degenerative process in RVOT and by the outgrowth tendency in children. However, at this point of discussion it has to be noted that the pulmonary valve implantation technique into the aortic position does not influence the durability of the RVOT conduit. This in principle depends on conduit diameter implanted, age, body surface and a type of the conduit. The exact mechanism of the RVOT conduit degeneration in the paediatric as well as in adult series has yet to be explored, and general consensus is that development of more durable conduits for RVOT reconstruction is needed [25, 26].

To conclude, we can state that our results support the excellence of the Ross procedure over 10 years, with overall survival >90%. It seems that the root replacement technique has a slight advantage over the sub-coronary implantation technique in the short term. This advantage is more obvious over 10 years in the mixed series for survival, the neoaorta reoperation rate, RVOT reoperation rate and for the freedom from the major cardiovascular events. The advantage of the root replacement technique may not be stated for sure in paediatric as well as in adult series, because of lack of series with long-term results. However, the tendency of better outcomes of root replacement is marked at 10 years.

In our investigated population, the mean age was 30.9 ± 11.7 (range, 8–50) years, what may be considered a middle young aged population with considered repartition of adults. Comparing the reoperation rate on neoaorta following the Ross procedure with reoperation for mechanical and biological aortic valve replacement in young/middle-aged adults, we can say that the Ross procedure is of a definitive advantage. In a middle-aged population, the reoperation more than 10 years after mechanical prosthesis may reach up to 10%. In case of bioprosthesis, this may be up to 30% [27, 28] at 10 years, and 50% at 15 years [29]. According to our analysis freedom from overall reintervention regarding the neoaorta and RVOT conduit replacement is superior to 93%. Freedom of root replacement is superior to 93% in all three groups and freedom from reintervention on RVOT in adult and mixed series is higher than 95 and 93%, respectively. In paediatric, series this is with 90% slightly lower.

These superior results in the recent report indicate a Ross procedure as the first line choice for aortic valve replacement in children, young adults and the middle-aged patients. This becomes important in young females of childbearing age and in young adults, because of lack of life-long anticoagulation and accompanying complications. Namely, yearly risk for major thromboembolic event and bleeding is about 2.8 to 3% per year in mechanical and 1.5 to 2% in biological valve [30]. To note is that biological valve, according to recent recommendations, are implanted in patients with age more than 60 years [31]. In this patient population, other reasons for thromboembolic events have to be considered, for example, atrial fibrillation. Risk is cumulative and linear; in other words, patients who undergo mechanical aortic valve replacement at the age of 45 will suffer a stroke or another major thromboembolism or haemorrhagic event by the age of 75 [28]. However, to clearly address the superior results of the Ross procedure, as double valve intervention in young adults over those of commercial available bioprosthesis, further clinical randomized trails has to be done.

**Conflict of interest**: None declared.

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